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The Cyclus Fuel Cycle Simulator and Applications of Cyclus for International Safeguards

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May 11, 2021

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

Outline of Part I: Nuclear Fuel Cycle Simulators: What and Why

Outline of Part II: Trailmap: Applying Cyclus to International Safeguards

Part I

Nuclear Fuel Cycle Simulators: What and Why

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Fuel Cycle Simulators Track Flows of Nuclear Material

- System-scale tool to model nuclear material flow between facilities
- Can be as simple as an Excel spreadsheet
- Most common usage is transition studies
- Should be able to inform non-technical as well as technical decision-makers

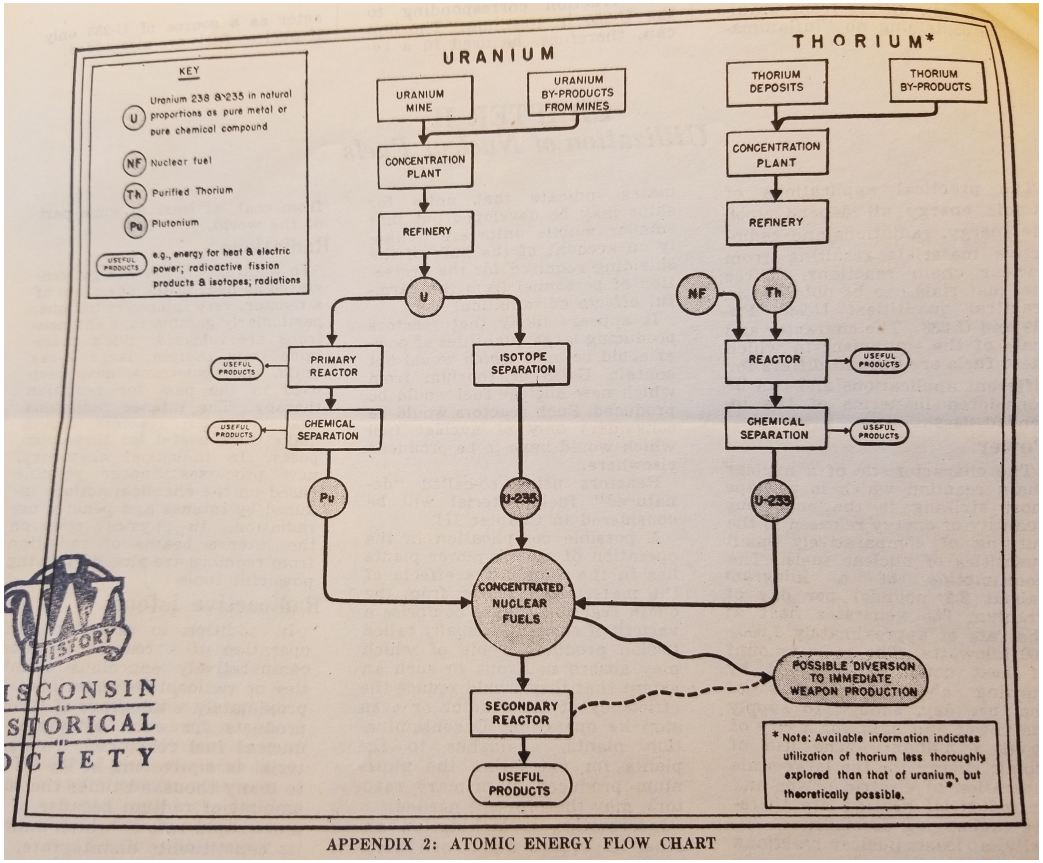

Figure: U.N. Report, Scientific and Technical Aspects of the Control of Atomic Energy, 1946 [1]

Transition Studies Require Dynamic (Time-Dependent) Capabilities

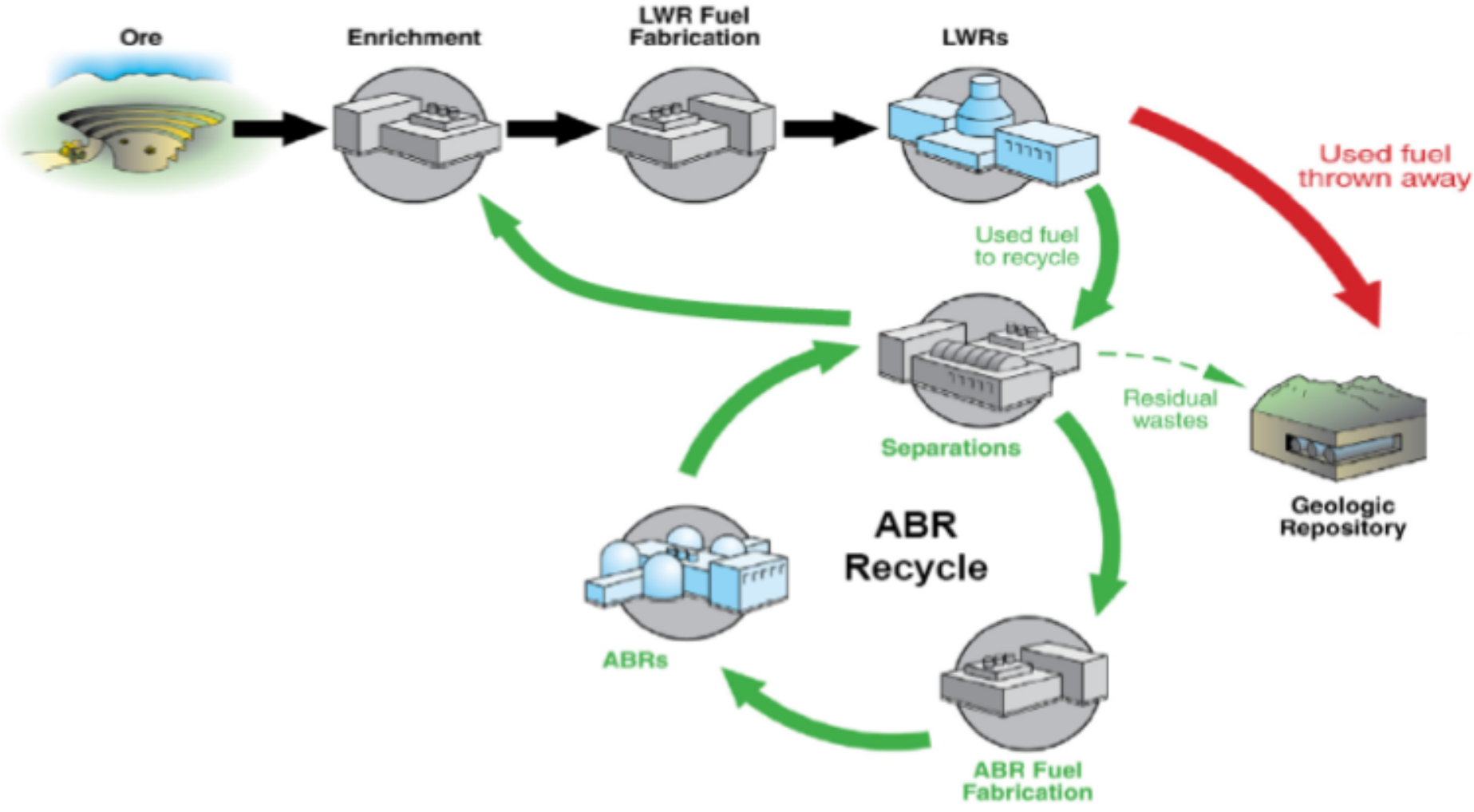

Figure: Classic usage of a fuel cycle simulator includes designing a timeline of new facilities and retirements to transition to a new fuel cycle

An Incomplete List of Fuel Cycle Simulators

Tool	Developer	Access	Dynam/ Static	Update?	First Pub
CAFCA [2]	MIT	Licensed (f)	D	Dormant	2004
CLASS [3]	France	Open-source	D	Yes	2013
COSI [4], [5]	CEA	Proprietary	D	Yes	1991
Cyclus [6]	UW–Madison	Open-source	D	Yes	2011
DANESS [7]	Nuclear21	Proprietary	D	Yes	2003
DESAE [8]	IAEA INPRO	Unknown	D	D	2006
DYMOND [9]	ANL	Proprietary	D	Yes	2001
FUTURE [10]	Korea	Unknown	D	Yes	2013
MAKAL [11]	IEA	Proprietary	D	Yes	1970s
NFCSim [12]	LANL	Proprietary	D	No	2005
NFCSS [13]	IAEA	Open GUI	S	Yes	1996
ORION [14]	ORNL/UKNNL	Proprietary	D	Yes	2007
ROADMAP [15]	IAEA	Unknown	U	Yes	2018
SITON [16]	Hungary	Unknown	D	Yes	2017
VISION [17]	INL	Licensed (f)	D	Yes	2006
VEGAS [18]	UT–Austin	Licensed (f)	D	Uknown	2017

Why another fuel cycle simulator?

Gaps were noted in fuel cycle simulation capabilities during the Global Nuclear Energy Partnership (GNEP) push of the late 2000s

- Proprietary tools
- Mostly focused on reactor simulations
- Limited or on ability to novel designs
- Static systems

GNEP in a few words

GNEP began in 2006 as a US-lead effort to expand nuclear energy domestically & internationally to:

- Reduce usage on fossil fuels/promote clean energy
- Encourage proliferation-resistant designs
- Assert US dominance as global supplier

US effort killed by Obama admin amid the Great Recession, international effort replaced by IFNEC

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History and Goals of Cyclus

- Successor to Global Evaluation of Nuclear Infrastructure Utilization Scenarios (GENIUS) tools

Goal: Flexibility

- Model innovative/unconventional technologies
- Minimal inherent technology assumptions

Goal: Modeling

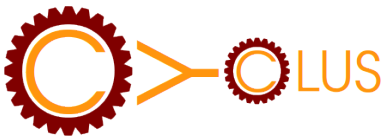
- Discrete facilities with discrete material tracking
- Optimization and sensitivity analysis

Goal: Software

- Low barrier to adoption with rapid payback[1]
- Commonly and freely available software infrastructure, can run on all operating systems

[1] The goal we're probably furthest from at this moment

Cyclus Overview [6]



- Open source modular fuel cycle simulator
- Market-based exchange of resources (commodities)
- Discrete facilities (even when identical)
- Discrete material tracking at the nuclide level
- Time-dependent
- Parallelizable

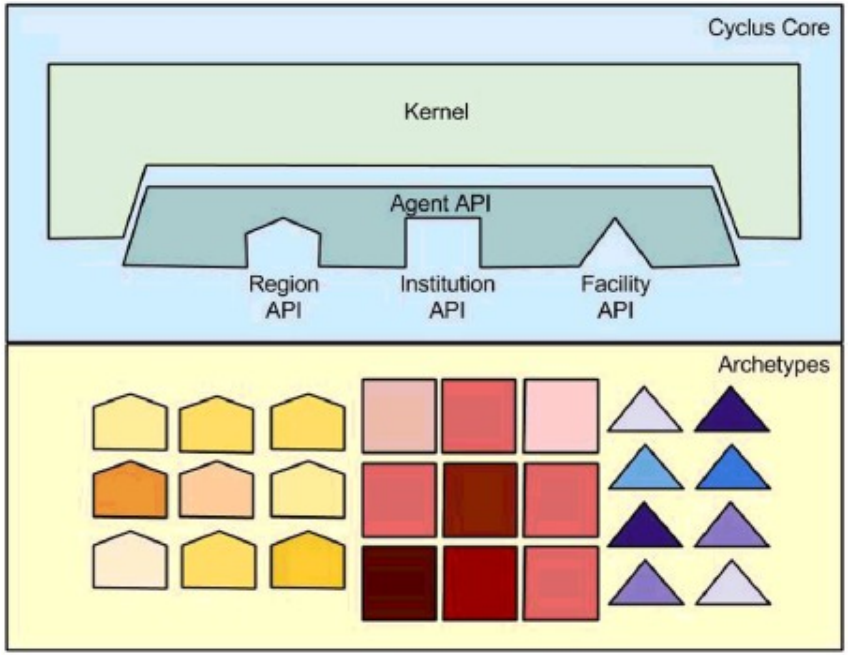


Figure: From *Fundamental concepts in the Cyclus nuclear fuel cycle simulation framework* by Huff *et al.* [6]

Agent-based model

- Cyclus coordinates and tracks the **deployment of facilities** and **movement of materials between facilities**
- Facility models are "plug and play" through the API
- Allow for easy switch between lower and higher fidelity
- Similar to MOOSE framework collaboration

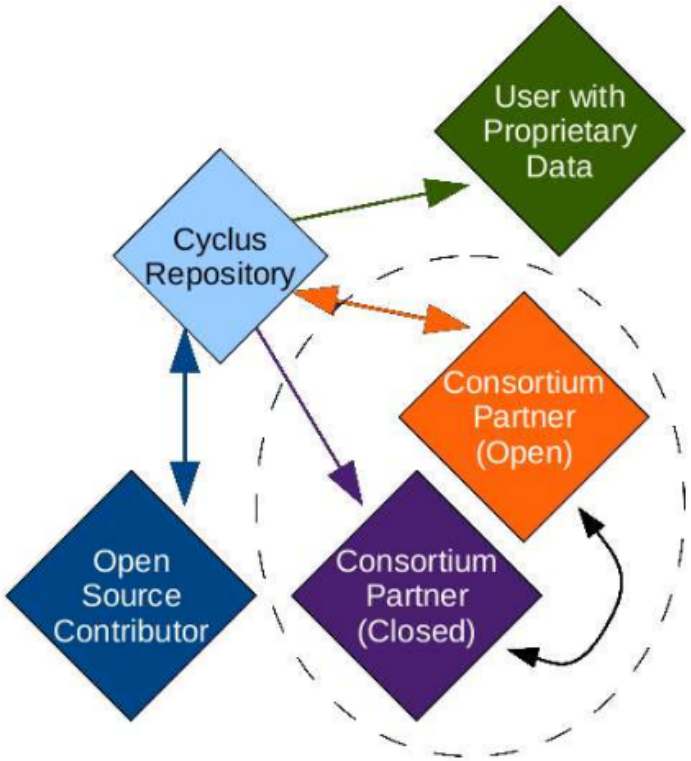


Figure: Cyclus architecture encourages open collaboration while allowing closed development and users with sensitive information, image from [6]

Cyclus facility models

- Cycamore includes simple models of common fuel cycle facilities
- Developers have contributed higher fidelity models such as
  - cyborg (Univ. of Tennessee)
  - mbmore (Univ. of Wisconsin)
- Anyone can develop an archetype
  - Open and closed contributors, models (archetypes), and users

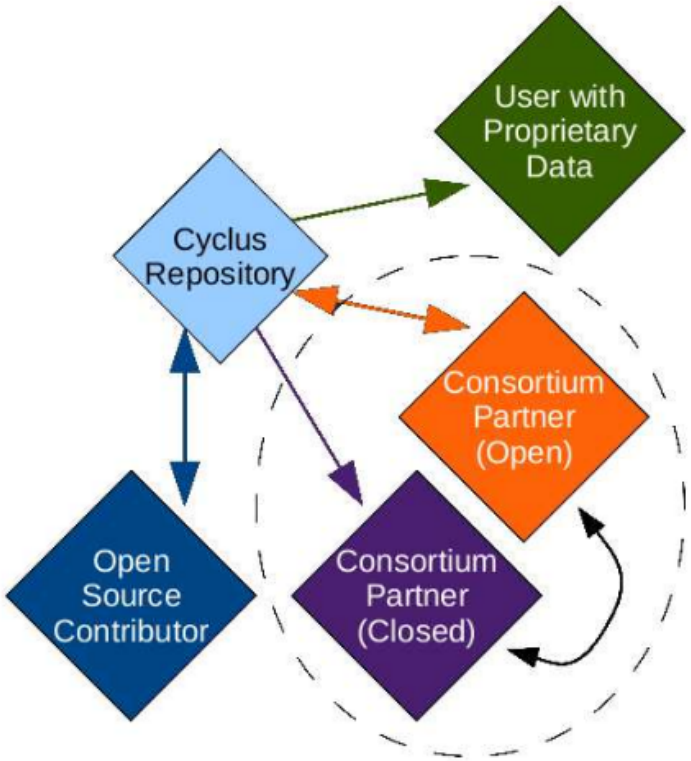


Figure: Cyclus architecture encourages open collaboration while allowing closed development and users with sensitive information, image from [6]

Dynamic Resource Exchange

- Market-based exchange of resources (commodities)
  - Nuclear materials
  - Knowledge, design information, experts
  - Economic units, money
- At every timestep, Cyclus gathers information about commodity requests
  - Quantity
  - Quality (isotopics)
  - Can be XOR, such as MOX or UOX
- Cyclus then gathers bids and solves the flow graph
- Materials are transferred and the simulation moves forward to the next timestep

Regions and Institutions

- Reflects the geopolitical realities of nuclear facilities
- Hierarchy is Region, Institution, Facility
- Region: State, could also be a geographical region smaller (e.g. the Midwest), or larger (e.g. Scandinavia) than a State
- Institution: utility or government
- Institutions deploy facilities
- Flow can be prioritized within institution/region
- Institutions can reject material outside desired characteristics (e.g. above 5% enriched) from other institutions
- Can be ignored (set to Null) if not relevant for a given simulation

Cyclus Community

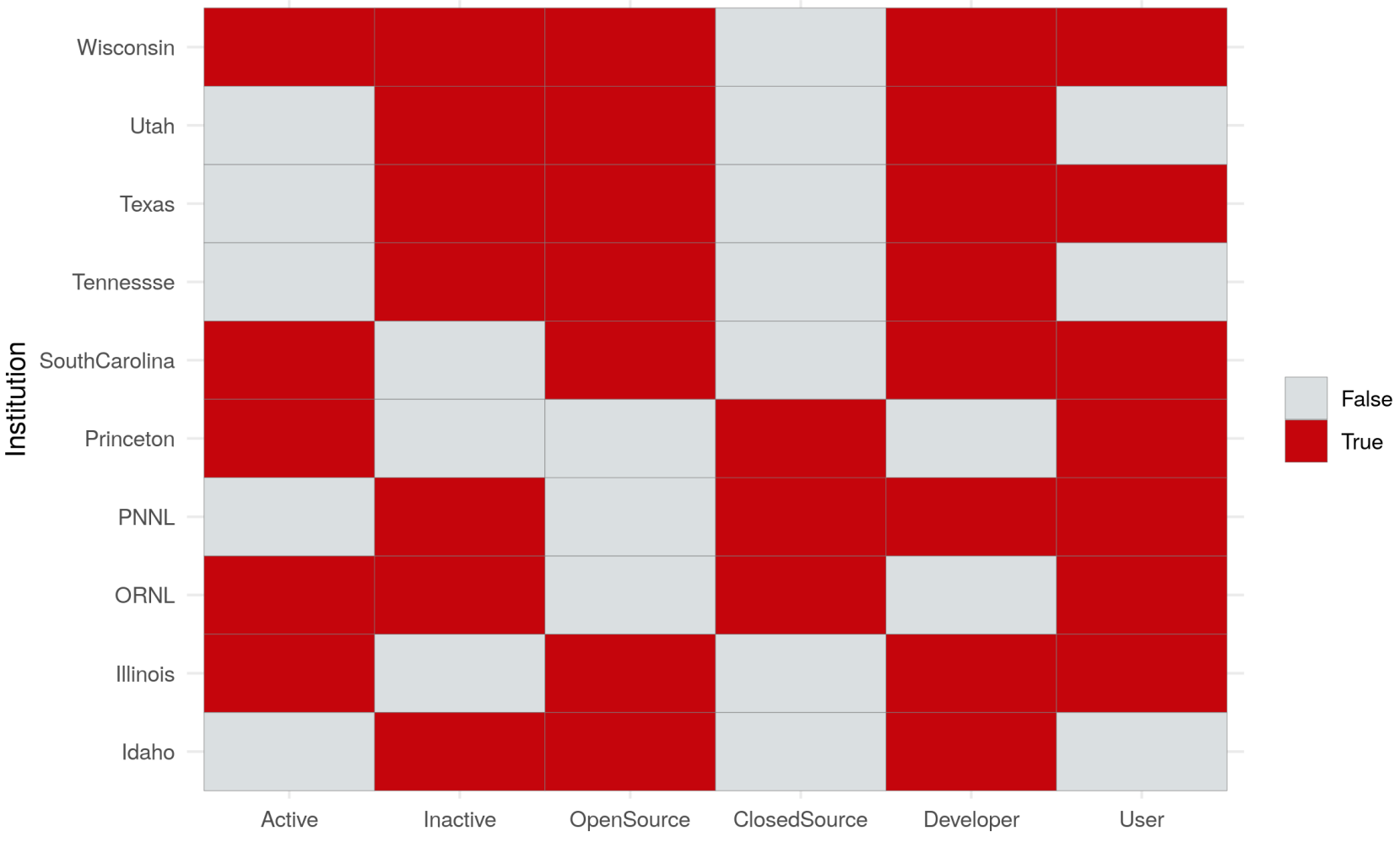


Figure: Community is mainly university, national lab

Cyclus Funders

Diverse albeit intermittent funding sources over the last decade

Part II

Trailmap: Applying CYCLUS to International Safeguards

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Motivation

Acquisition Pathway Analysis (APA)

Assess technically plausible steps a State could take to acquire material that could be used in a nuclear explosive device [19]

- Objective and reproducible analysis for any set of fuel cycle facilities and capabilities
- Bring experience in modeling nuclear material flows to the nonproliferation and safeguards community [20]

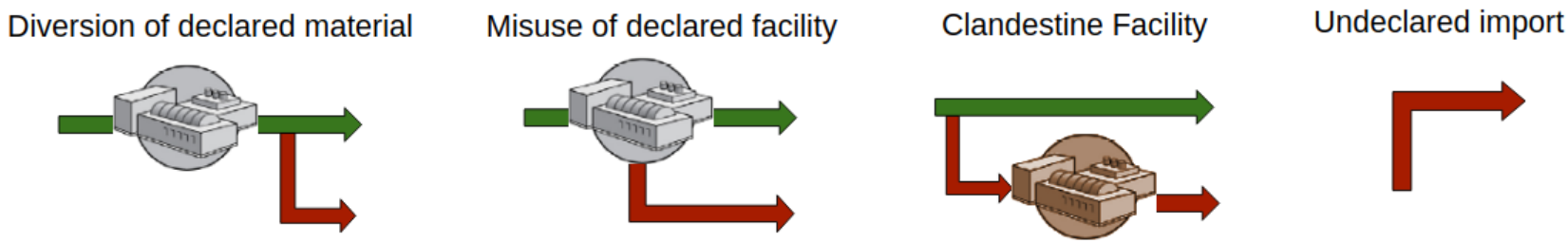

Figure: Four path steps to capture, based on [21]

Introducing Trailmap

- Trailmap is a new Cyclus module to conduct APA

Before running Trailmap

- User gathers State-specific factors and information
- Creates a Cyclus input file with the set of existing facilities as well as technologically feasible undeclared activities and facilities

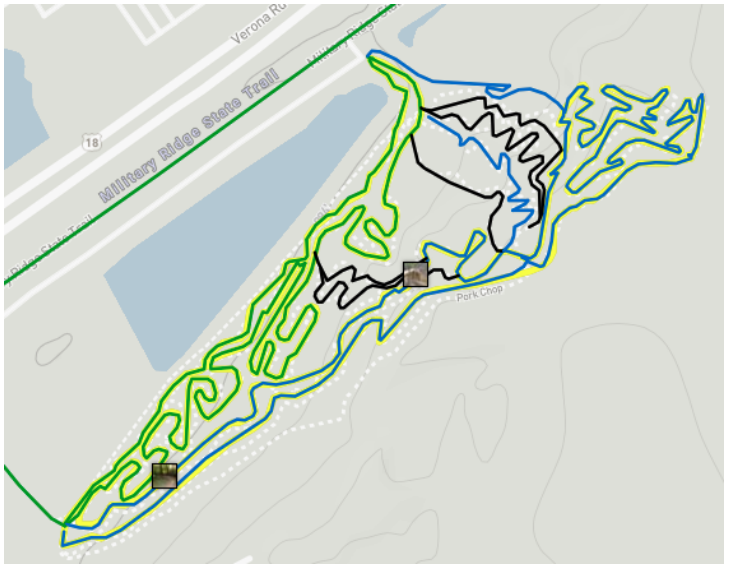

Figure: From MTB Project

Trailmap is also open-source and is available at https://github.com/cnerg/trailmap

Trailmap

1. Identify installed Cyclus modules
2. Reads in Cyclus input file, identifying agents and commodities
3. Builds a directed graph $G = (V,\ E)$ of facilities and commodities using NetworkX
4. Depth-first search from all sources to all sinks
5. Visualize graph using Jupyter notebook
6. Filter and sort pathways using analysis tools
7. Run Cyclus for individual path or groups of paths

Future work

7. Further sorting and filtering of pathways based on throughput
8. Test notional safeguards

Example "Republic of Bundy"

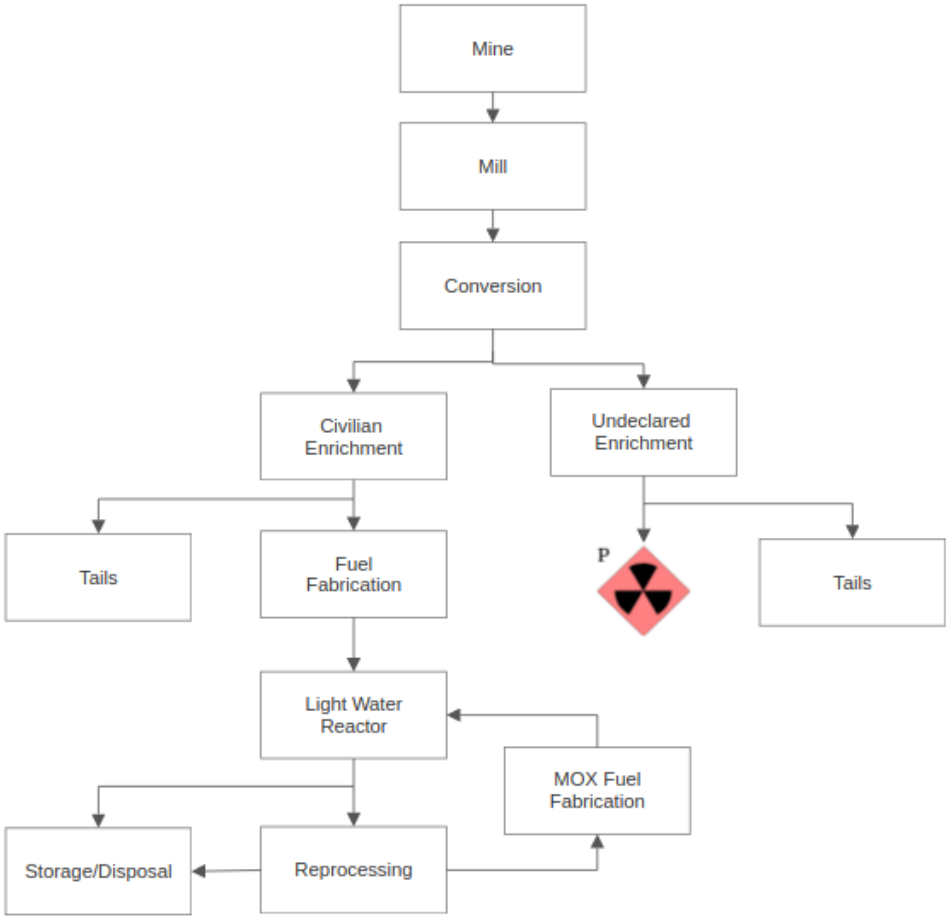

Figure: Network flow of "ROB" fuel cycle

- Small but well-developed fuel cycle
- Civilian declared enrichment and reprocessing
- Clandestine enrichment facility

Figure: Former foster dog Bundy

Acquisition Paths produced by TRAILMAP

- Mine, Mill, Conversion, Declared Enrichment, Tails
- Mine, Mill, Conversion, Undeclared Enrichment, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Waste Storage, Reprocessing, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Reprocessing, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Enrichment, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Waste Storage, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, HEU/Pu
- Mine, Mill, Conversion' Declared Enrichment, Undeclared Enrichment, Undeclared Tails,
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Tails

Acquisition Paths produced by TRAILMAP: Removing unde

- ~~Mine, Mill, Conversion, Declared Enrichment, Tails~~
- Mine, Mill, Conversion, Undeclared Enrichment, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Waste Storage, Reprocessing, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Reprocessing, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Enrichment, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Waste Storage, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, HEU/Pu
- ~~Mine, Mill, Conversion' Declared Enrichment, Undeclared Enrichment, Undeclared Tails~~
- ~~Mine, Mill, Conversion, Declared Enrichment, Undeclared Tails~~

Facility-specific pathways: reprocessing

- ~~Mine, Mill, Conversion, Declared Enrichment, Tails~~
- Mine, Mill, Conversion, Undeclared Enrichment, HEU/Pu
- **Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Waste Storage, Reprocessing, MOX Fuel Fab, HEU/Pu**
- **Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Reprocessing, MOX Fuel Fab, HEU/Pu**
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- Mine, Mill, Conversion, Declared Enrichment, HEU/Pu
- ~~Mine, Mill, Conversion' Declared Enrichment, Undeclared Enrichment, Undeclared Tails~~
- ~~Mine, Mill, Conversion, Declared Enrichment, Undeclared Tails~~

Filtering: shortest pathways

- ~~Mine, Mill, Conversion, Declared Enrichment, Tails~~
- Mine, Mill, Conversion, Undeclared Enrichment, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Waste Storage, Reprocessing, MOX Fuel Fab, HEU/Pu
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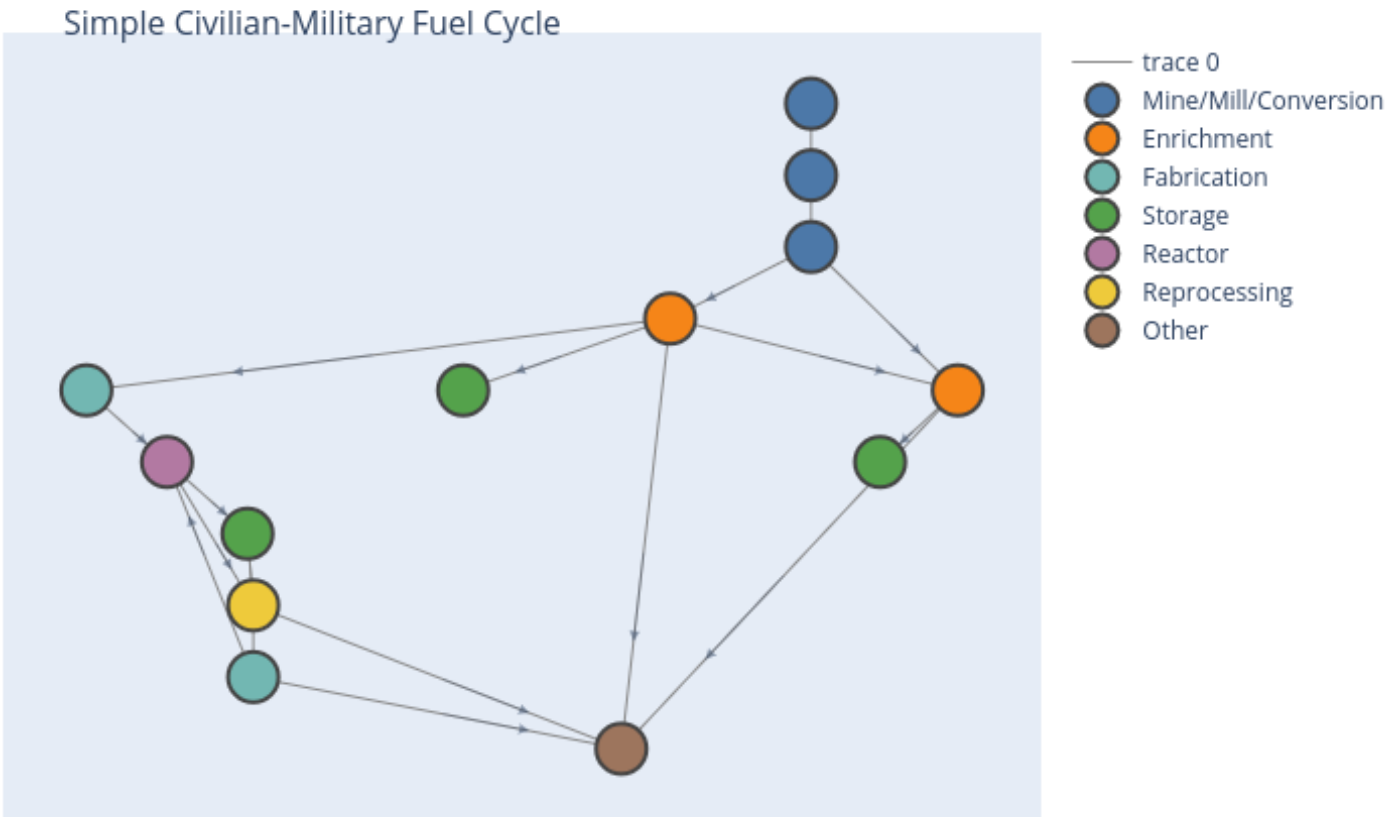
- Mine, Mill, Conversion, Declared Enrichment, HEU/Pu
- ~~Mine, Mill, Conversion' Declared Enrichment, Undeclared Enrichment, Undeclared Tails~~
- ~~Mine, Mill, Conversion, Declared Enrichment, Undeclared Tails~~

Other Tools

- Search over a given list of facilities
  - Pathways that contain *any* facilities in the list
  - Pathways that contain *all* facilities in the list
- Pathways that flow between a specific source and/or target node
  - Node disjoint paths
- Cyclical or looping pathways (reprocessing)
- Graph parameters
  - Graph semiconnectedness
  - Flow hierarchy
  - Shortest, longest paths
- Flow (throughput)
  - Flow of a given pathway
  - Maximum total flow (complete breakout)
  - Maximum flow pathway
  - All pathways with flow above a threshold

Visualizing

- Automated interactive visualization using Jupyter Notebooks and Plotly package
- Graphviz 'dot' to layout nodes
  - Good starting point, designed for trees
  - NFC are not quite trees, but almost



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Summary

- TRAILMAP can conduct APA
- Basic interactive visualization is running, current effort to add functionality with a freshman undergrad researcher
- TRAILMAP is mostly a command-line tool right now, but can also be used from a Jupyter Notebook
  - Does require working CYCLUS install, which is only available for Linux and MacOS. Can be used in a Docker container
- Next up:
  - Automating import of throughput information from CYCLUS simulation into TRAILMAP
  - Calculating time to completion for paths of interest
  - Revamp visualization tool

Current Effort (LANL work)

- Can patterns of nuclear material movement in a State be simulated with a high enough fidelity to be able to identify discrepancies?
  - Generating synthetic transaction data to produce synthetic material balance reports
  - CYCLUS is not intended to identify instances of diversion, rather to note discrepancies that may be investigated further

Receiver	ReceiverPrototy	SenderI	SenderPrototy	Transac	Resourc	Commod	Time	ObjId	Quantity	Units	QualId	Parent1	Parent2	100100	9223500	9223800
19	Enrichment	18	Source	12	94	natl_u	6	58	63	kg	1	0	0	0	0.007	0.993
20	Sink	21	Reactor	17	77	waste	6	41	2	kg	3	64	0	1	0	0
20	Sink	22	Reactor	19	78	waste	6	43	2	kg	3	70	0	1	0	0
20	Sink	23	Reactor	18	79	waste	6	45	2	kg	3	76	0	1	0	0
21	Reactor	19	Enrichment	14	100	enriched_u	6	60	2	kg	23	97	0	0	0.045	0.955
22	Reactor	19	Enrichment	16	106	enriched_u	6	62	2	kg	24	103	0	0	0.045	0.955
23	Reactor	19	Enrichment	15	112	enriched_u	6	64	2	kg	25	109	0	0	0.045	0.955
24	Reactor	19	Enrichment	13	118	enriched_u	6	66	2	kg	26	115	0	0	0.045	0.955
19	Enrichment	18	Source	20	139	natl_u	7	81	84	kg	1	0	0	0	0.007	0.993
20	Sink	21	Reactor	27	119	waste	7	60	2	kg	3	100	0	1	0	0
20	Sink	22	Reactor	29	120	waste	7	62	2	kg	3	106	0	1	0	0
20	Sink	23	Reactor	28	121	waste	7	64	2	kg	3	112	0	1	0	0
20	Sink	24	Reactor	21	122	waste	7	66	2	kg	3	118	0	1	0	0
21	Reactor	19	Enrichment	23	145	enriched_u	7	83	2	kg	32	142	0	0	0.045	0.955
22	Reactor	19	Enrichment	25	151	enriched_u	7	85	2	kg	33	148	0	0	0.045	0.955
23	Reactor	19	Enrichment	24	157	enriched_u	7	87	2	kg	34	154	0	0	0.045	0.955
24	Reactor	19	Enrichment	22	163	enriched_u	7	89	2	kg	35	160	0	0	0.045	0.955
25	Reactor	19	Enrichment	26	169	enriched_u	7	91	2	kg	36	166	0	0	0.045	0.955
19	Enrichment	18	Source	30	193	natl_u	8	108	105	kg	1	0	0	0	0.007	0.993

Figure: Transaction data from an example input file

Conclusions

- Cyclus holds promise for the safeguards community,
  - ...but further development is still needed
  - ...and we're looking for collaborations to ensure our software is useful and relevant
- The entire Cyclus ecosystem was designed with flexibility and ongoing development in mind

Feedback encouraged!

Can you see a use for Cyclus in your work, or an area for Cyclus to develop into? Please let me know! mummah@lanl.gov

Also, if you know anything about the current or historical state of NFCSim, please let me know!

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  - G. T. Seaborg Institute
  - Nuclear Criticality Safety Program

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